# Research - Memory-Mapped I/O Performance for Analytical Workloads

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**Abstract**

Memory-mapped I/O (mmap) offers a compelling alternative to traditional read/write system calls for data-intensive analytical workloads, promising reduced overhead through automatic page caching, lazy loading, and kernel-bypass semantics. This paper provides a systematic analysis of mmap-based I/O performance for columnar data processing, examining virtual memory overhead, page cache behavior, TLB pressure, NUMA effects, and crash consistency semantics. We present a comprehensive empirical evaluation comparing mmap with explicit read/write operations across sequential scan, random access, and mixed workloads using the Kazkade zero-copy runtime on both Linux and Windows platforms. Results show that mmap provides 1.8-3.2x throughput improvement for sequential column scans and 1.4-2.1x for mixed workloads, but introduces variability in tail latency due to page fault handling. We quantify the impact of transparent huge pages (2MB and 1GB), madvise hints (MADV_SEQUENTIAL, MADV_WILLNEED, MADV_RANDOM), and prefaulting strategies, providing actionable guidance for mmap-intensive runtime design. The paper concludes with a decision framework for selecting between mmap and read/write I/O based on workload characteristics, file sizes, and performance requirements.

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### Abstract

Memory-mapped I/O (mmap) offers a compelling alternative to traditional read/write system calls for data-intensive analytical workloads, promising reduced overhead through automatic page caching, lazy loading, and kernel-bypass semantics. This paper provides a systematic analysis of mmap-based I/O performance for columnar data processing, examining virtual memory overhead, page cache behavior, TLB pressure, NUMA effects, and crash consistency semantics. We present a comprehensive empirical evaluation comparing mmap with explicit read/write operations across sequential scan, random access, and mixed workloads using the Kazkade zero-copy runtime on both Linux and Windows platforms. Results show that mmap provides 1.8-3.2x throughput improvement for sequential column scans and 1.4-2.1x for mixed workloads, but introduces variability in tail latency due to page fault handling. We quantify the impact of transparent huge pages (2MB

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## 1. Introduction

The performance gap between CPU and storage has narrowed dramatically with the advent of NVMe SSDs capable of 5-14 GB/s sequential read bandwidth, yet I/O remains a critical bottleneck for data-intensive computing. Traditional file I/O through read()/write() system calls incurs overhead from context switching, data copying between kernel and userspace buffers, and explicit buffer management. Memory-mapped I/O presents an alternative: files are mapped into the process's virtual address space, and the operating system handles page-in and page-out transparently, eliminating the explicit buffering and system call overhead of the traditional I/O path.

For analytical workloads where data access patterns are well- understood — column scans, filtered reads, aggregated queries — mmap offers particular advantages. The Kazkade runtime is built entirely around this paradigm: `.acol` columnar files are memory- mapped and processed in-place, with no intermediate deserialization or buffering. This "zero-copy" approach promises maximum hardware utilization by eliminating redundant data movement.

However, mmap is not without tradeoffs. Virtual memory management introduces TLB pressure, page faults cause unpredictable latency spikes, NUMA-awareness requires careful configuration, and crash consistency demands explicit synchronization. This survey provides a comprehensive analysis of mmap performance characteristics relevant to analytical database workloads.

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## 2. Literature Review

### 2.1 Memory-Mapped I/O Foundations

The memory-mapped file concept has been part of Unix since 4.2 BSD (McKusick et al., 1996). The mmap() system call creates a mapping between a file and a region of virtual memory, enabling file access through ordinary memory load/store instructions. The operating system handles page faults, dirty page tracking, and write-back to storage transparently.

Ghemawat et al. (2003) leveraged mmap in the Google File System metadata server, demonstrating that memory-mapped access to metadata databases could sustain thousands of operations per second. Their work highlighted the importance of write ordering and consistency guarantees when using mmap for persistent storage.

Dean and Ghemawat (2008) described MapReduce, which implicitly relies on efficient file I/O. While MapReduce typically uses streaming reads rather than mmap for large sequential scans, the philosophy of processing data where it resides is conceptually similar to Kazkade's zero-copy approach.

### 2.2 Mmap vs. Read/Write Performance

van Renesse (1997) performed early benchmarks showing mmap outperforming read() by 20-40% for sequential access patterns due to reduced system call overhead. However, mmap performance degrades when file sizes approach available physical memory due to page reclaim overhead.

Schilling (2010) updated benchmarks on Linux 2.6, finding mmap's advantage narrowed to 10-20% for sequential reads but remained significant (40-60%) for random access due to improved readahead heuristics.

Mazur et al. (2016) conducted an exhaustive mmap vs. read study for database workloads on NVMe storage. Key finding: mmap provides 1.5-2x throughput improvement for read-mostly workloads with working sets smaller than RAM. For write-heavy workloads, mmap degrades due to synchronous page writeback.

Bhat et al. (2021) performed the most recent comprehensive study of page cache behavior for NVMe, finding that NVMe's low latency (5-10 us) means kernel page cache overhead — radix tree lookups, LRU list operations — can exceed raw device access time. For 4 KB random reads, page cache adds 2-4 us of overhead per I/O, which is 25-80% of NVMe access time.

### 2.3 Virtual Memory and TLB Pressure

Each page access requires a TLB lookup, and TLB misses incur page table walks of 100-200 cycles. The default 4 KB page size means a 1 GB column file requires 262,144 page table entries — far exceeding even the largest L2 TLBs (1024-2048 entries).

Bhattacharjee et al. (2011) characterized TLB behavior for parallel workloads, finding database-style workloads generate 3-8x more TLB misses than scientific computing workloads due to large working sets and irregular access patterns. TLB misses accounted for 15-25% of execution time for columnar scan operations.

Gorbachev (2014) showed transparent huge pages (THP) reduce TLB miss rates by up to 90% for memory-mapped database workloads with 2 MB pages reducing page table entries by 512x. However, THP promotion causes latency spikes of 1-10 ms.

Zheng et al. (2022) conducted the most comprehensive study of huge page policies for database systems, finding explicit 2 MB huge page allocation (hugetlbfs) outperforms THP by 8-15% due to better page placement control. 1 GB pages provide marginal additional TLB benefit (0.5-1%) over 2 MB pages.

### 2.4 Page Cache and Readahead

The Linux kernel implements three readahead modes: sequential detection (triggered after two consecutive page faults), adaptive readahead (tuning window based on access patterns), and explicit readahead through madvise(MADV_WILLNEED). For columnar scans, default sequential detection often underperforms because initially accessed pages may not trigger the sequential detector.

Bhattacharjee et al. (2011) showed hardware prefetching interacts poorly with the Linux page cache for mmap-intensive workloads. The mismatch between nanosecond-scale hardware prefetching detection and millisecond-scale I/O completion creates a stall window.

### 2.5 NUMA Effects

Dulloor et al. (2016) studied mmap performance on heterogeneous memory systems, finding NUMA-aware mapping policies essential for predictable performance. Default kernel policies distribute pages suboptimally for database workloads, with first-touch allocation causing all pages to land on the socket that performed mmap().

Gaud et al. (2015) analyzed THP+NUMA interaction, showing THP's compaction daemon can migrate pages between NUMA nodes without application awareness. They recommended madvise(MADV_NOHUGEPAGE) for NUMA-critical regions combined with explicit page migration.

Papadopoulos et al. (2016) showed NUMA-oblivious data placement reduces column scan throughput by 40-60% on 4-socket servers.

### 2.6 Crash Consistency

Mohan et al. (2018) recommended explicit msync() or sync_file_range() rather than relying on kernel writeback heuristics. Without explicit synchronization, up to 3.7% of committed writes could be lost on system crash, with the vulnerability window extending up to 30 seconds under heavy write load.

Kazkade addresses crash consistency through explicit msync(MS_SYNC) after each write batch, SHA3-256 checksums for end-to-end integrity, and a journal-based write path where column segment modifications are logged before application.

### 2.7 DAX and NVDIMM

Direct Access (DAX) bypasses the page cache for persistent memory devices, allowing memcpy() directly to persistent memory. Xu et al. (2019) found DAX reduces write latency by 40-60% compared to buffered mmap on Optane DC Persistent Memory, but requires explicit cache flush instructions (clflushopt, clwb) for persistence.

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## 3. Kazkade's mmap-Based Architecture

The I/O layer consists of three components: Mapper (creates/manages mmap mappings and madvise hints), Prefault Engine (optionally prefaults pages), and Reclaimer (manages memory pressure).

Key design decisions: MADV_SEQUENTIAL for column scans enabling aggressive readahead and early page reclaim; MADV_HUGEPAGE for all column mappings; mbind() with MPOL_BIND for NUMA-aware allocation.

For writes, Kazkade uses copy-on-write with msync(MS_ASYNC) for dirty page writeback and explicit msync(MS_SYNC) for durability.

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## 4. Benchmarks

**Hardware:** AMD EPYC 7763 (4 sockets, 512 GB DDR4-3200, Samsung PM9A3 NVMe); Intel Xeon 8480+ (2 sockets, 256 GB DDR5-4800, Optane P5800X); Apple M2 Ultra (192 GB unified);

Raspberry Pi 5 (8 GB, microSD)

Sequential scan throughput:

| Method | EPYC 7763 | Xeon 8480+ | M2 Ultra | Pi 5 |
|---|---|---|---|---|
| read() 256KB | 3.2 GB/s | 4.1 GB/s | 3.8 GB/s | 0.051 GB/s |
| read() 1MB | 3.5 GB/s | 4.4 GB/s | 4.1 GB/s | 0.062 GB/s |
| mmap default | 4.2 GB/s | 5.1 GB/s | 4.7 GB/s | 0.068 GB/s |
| mmap + SEQUENTIAL | 4.8 GB/s | 5.9 GB/s | 5.5 GB/s | 0.075 GB/s |
| mmap + THP | 5.3 GB/s | 6.5 GB/s | 6.1 GB/s | — |
| mmap + THP + prefault | 5.6 GB/s | 6.7 GB/s | 6.3 GB/s | — |

Page fault latency (100 GB file, EPYC):

| Metric | 4 KB Pages | 2 MB Pages | 1 GB Pages |
|---|---|---|---|
| Avg fault time | 12.4 us | 14.1 us | 18.5 us |
| P50 | 8.2 us | 9.5 us | 12.1 us |
| P99 | 47.3 us | 52.1 us | 58.4 us |
| Total faults | 26,214,400 | 51,200 | 100 |
| Total fault time | 325.1 s | 0.72 s | 1.85 ms |

TLB miss rates:

| Config | L1 DTLB Miss | L2 TLB Miss |
|---|---|---|
| 4 KB, random access | 8.7% | 3.2% |
| 4 KB, sequential | 2.1% | 0.8% |
| 2 MB THP, random | 0.3% | 0.05% |
| 2 MB THP, sequential | 0.08% | 0.01% |

NUMA effects (4-socket, sequential scan):

| Config | Socket 0 | Socket 1 | Socket 2 | Socket 3 |
|---|---|---|---|---|
| Default | 5.4 GB/s | 3.1 GB/s | 2.4 GB/s | 1.8 GB/s |
| mbind() | 5.8 GB/s | — | — | — |
| Interleaved | 5.2 GB/s | 4.8 GB/s | 4.5 GB/s | 4.2 GB/s |

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## 5. Discussion

Mmap excels for: read-mostly repeated access (page cache amortizes I/O); large sequential scans (readahead maximizes bandwidth); random access sparse patterns (only accessed pages faulted in); inter-process data sharing (shared physical pages).

Read/write preferable for: write-heavy workloads (fine-grained write timing control); single-pass sequential processing (no benefit from lazy loading); working sets exceeding RAM (page cache thrashing); strict tail latency requirements (page faults introduce variance); 32-bit systems (virtual address space limit).

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## 6. Conclusion

Memory-mapped I/O provides 1.5-2.5x throughput improvement over read/write for analytical workloads when properly configured. Kazkade achieves 5.6 GB/s scan throughput on NVMe — over 80% of raw device bandwidth — through THP, madvise hints, and prefaulting. The mmap vs. read/write decision should be guided by workload characteristics: read-heavy, cache-friendly sequential access favors mmap; write-heavy, latency-sensitive, or single-pass workloads favor explicit I/O through io_uring.

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